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INTERCEPTION BY LOW ORBIT SATELLITE BORNE
INTERCEPTION DEVICES OF HIGH ORBIT SATELLITE

by

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ABSTRACT This paper analyzes the capability of low orbit satellite borne interception devices to carry out orbital maneuvers to intercept high orbit satellites. In interception system analysis, threat areas, defense areas, and intercept areas are three basic concepts. This article gives methods for their modeling as well as solution. In conjunction with this, use is made of digital simulation, giving standard threat areas, defense areas, and intercept areas corresponding to different intercept time periods.

KEY TERMS Satellite orbit, Space flight interception device, Intercept trajectory

GRAPHICS DISCLAIMER

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I. THE CONCEPTS OF THREAT AREAS, DEFENSE AREAS, AND INTERCEPT AREAS

Interception of high orbit satellites by low orbit satellite borne interception devices is a "space based-space based" intercept system. Intercept systems are composed of satellite platforms moving along respective orbits as well as interception devices I capable of orbital maneuver and carried on the platforms. Intercept targets are high orbit satellites SS. The intercept debris path is as shown in Fig.1. At the instant when τ*=0, SS moves along the orbit to point S. At the instant τ (illegible) arrives at point S. At instant τ(illegible) the satellite platform moves to point B. At this time, the satellite platform releases I. In accordance with guidance methods, I carries out orbital maneuver along a certain intercept orbit and also arrives at point S(illegible) at just the instant τ(illegible). The point S* is called the predicted hit point. At this point, I collides with SS, destroying the target.

Important concepts in intercept system analysis are threat areas, defense areas, as well as intercept areas. Definitions are as follows.

If one assumes that the instant when intercept begins is τ(illegible)=0, at this time, SS is located at point S, and the satellite platform is located at point B. Due to the fact that I orbital intersection maneuver capabilities are limited by the amount of fuel carried as well as other restrictions, speaking in terms of point S, therefore, there exists a zone where, if only the satellite platform is

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* Numbers in margins indicate foreign pagination. Commas in numbers indicate decimals.

positioned within this zone at instant τ(illegible)=0, and, in conjunction with this, I is released at this instant, going into orbital change maneuvers, it flies along a collision course. Only then is it possible to make I collide with SS at the instant τ^* . This zone is called the τ^* threat zone of SS. Obviously, satellite platforms outside τ(illegible) threat zones do not possess the capability of killing or damaging SS located at position S at instant $\tau^*=0$. The greater the number of satellite platforms is within the τ^* threat area, the greater, then, is also the number of I possessing the capability of killing or damaging SS at time τ^*. As a result, the greater is also the threat posed to SS. Because of this, speaking in terms of satellite platforms, threat areas determine whether or not the I they carry possess the capability to kill or damage SS. Speaking in terms of SS, threat areas determine the magnitude of the threats they pose as well as the locations on their own orbits giving rise to collisions (determined by τ(illegible)).

In the same way, with regard to satellite platforms at instant $\tau^*=0$ located on point B, there also exists a zone. Only when SS enters this zone at instant τ^* is it then possible to be killed or damaged by platforms. This zone is called the platform τ^* defense area. τ^* defense areas determine the size of platform operational ranges, that is, satellite platforms--after given intercept time periods τ^*--are only capable of killing or damaging SS that enter the areas in question. However, intercept areas, by contrast, are defined as the collection of all possible intercept collision points (that is, predicted hit points) for a certain platform and intercept time period τ^*. From a different angle, they reflect the size of platform operation ranges.

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τ^* threat areas, τ^* defense areas, and τ^* intercept areas--besides being related to intercept time periods τ^*--are also related to the locations of platforms and SS at instant τ^*, fuel carried by interception devices, as well as guidance methods. In this article, option is made for the use of speed gain guidance to act as the guidance method for I.

This article will give precise methods for the modeling and solution of these three types of zones. In conjunction with this--going through digital simulation--it will present classical τ^* threat areas, τ^* defense areas, and τ^* intercept areas.

II. RESEARCH ASSUMPTIONS, COORDINATE SYSTEMS, AND SATELLITE PLATFORM-I-SS KINEMATICS MODELS

(I) Assumptions

The entire interception process associated with low orbit satellite borne interception devices intercepting high orbit satellites occurs outside dense atmospheric layers. In research, the assumptions made are as follows:

1. Spacecraft fly outside the atmosphere. Satellite platforms and SS only undergo the effects of the earth's gravity. During flight processes, orbital maneuvers are not carried out. Besides undergoing the effects of the earth's gravity, I also undergo the effects of thrust. Thrust uses the form of impulses at points of orbital change to influence I, making I instantaneously achieve required velocity gains.

2. The globe is a sphere with radius R(illegible) = 6371110m. The gravitational field of the earth is an inverse square of the distance force field. The gravitational constant of the earth is μ=3.986005x1014m3/s2.

3. Disregard the effects of global rotation on spacecraft movements.

4. Satellite platforms are circular polar orbits with altitudes of H=640km. High orbit satellites are stationary equatorial satellites with orbital altitudes of H(illegible)=35787km. Maximum velocity impulses which interception devices are capable of supplying themselves are ▪Vmax=6421m/s.

(II) Coordinate Systems and Coordinate Transforms

1. In the geocentric inertial coordinate system OeXYZ, Oe is congruent with the center of the earth. The X axis in the equatorial plane points toward the vernal equinox. The Z axis and the direction of autorotation of the earth are the same. The Y axis is determined by a right hand rule, as shown in Fig.2.

2. As far as satellite platform orbit coordinate system Oe-XpYpZp is concerned, Xp is the direction of continuation of Oe and the instant τ*=0. Yp lies in the satellite platform orbital plane, points in the direction of flight, and is positive. Zp is determined by a right hand rule as shown in Fig.2.

3. With regard to interception orbit coordinate system OeXIYIZI, XI and Xp are congruent. YI lies in the plane of interception orbit, points toward the predicted target hit point S* , and is positive. ZI is determined by a right hand rule as shown in Fig.2. In order to facilitate the researching of problems one may as well assume that the position under the stars of the vernal equinox is just congruent with S* . Then, at the

instant $\tau^*=0$, SS should be positioned at the point S on the eastern equatorial radius $-n_{as}\tau^*$. In this,

$$n_{as} = \sqrt{\mu/(R_e + H_a)^3}$$

is the orbital angular velocity of SS.

4. Relationships Between Oe-XYZ and Oe-XpYpZp.

Taking Oe-XYZ and first turning it around the Z axis an angle Ω, then turning it around the new Y axis -uo, and finally turning 90° around the new X axis, it is then possible to obtain Oe-XpYpZp. Coordinate transform relationships then are:

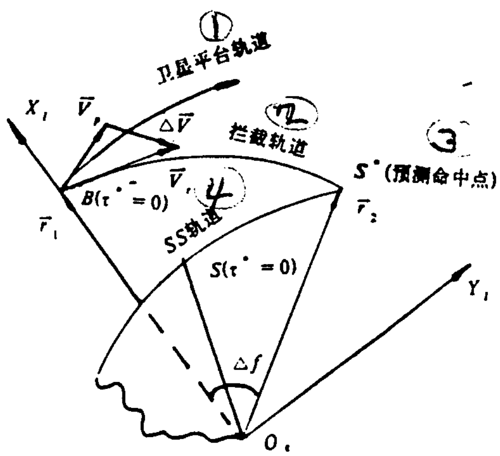
(1) $$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \cos\Omega\cos u_0 & -\cos\Omega\sin u_0 & \sin\Omega \\ \sin\Omega\cos u_0 & -\sin\Omega\sin u_0 & -\cos\Omega \\ \sin u_0 & \cos u_0 & 0 \end{bmatrix} \begin{bmatrix} X_p \\ Y_p \\ Z_p \end{bmatrix} = A \begin{bmatrix} X_p \\ Y_p \\ Z_p \end{bmatrix}$$

In this, Ω and uo are the longitude and latitude associated with I at instant $\tau^*=0$. /41

5. Relationships Between Oe-XIYIZI and Oe-XpYpZp.

The included angle between intercept orbit planes and satellite platform orbit planes are α. Turning XpYpZp around Xp by α, one obtains Oe-XIYIZI. The coordinate transform relationships then are:

$$
(2) \qquad \begin{bmatrix} X_p \\ Y_p \\ Z_p \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} X_I \\ Y_I \\ Z_I \end{bmatrix} = B \begin{bmatrix} X_I \\ Y_I \\ Z_I \end{bmatrix}
$$



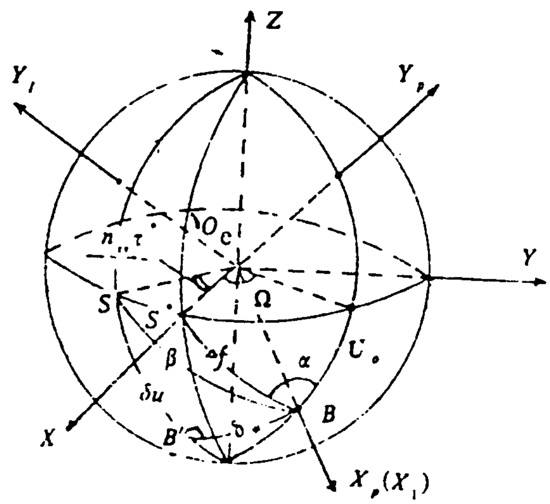


Fig.1 Intercept Process Schematic

Key: (1) Satellite Platform Orbit (2) Intercept Orbit (3) Predicted Hit Point (4) Orbit

Fig.2 Schematic Diagram of Threat Area, Defense Area, and Intercept Area Determination

In this, α is capable of being solved for from the relationships set out below:

For $-90° < u_o < 0°$, $tg\Omega = tg\alpha \sin(-u_o)$;

For $-270° < u_o < -90°$, $ctg\alpha = ctg\Omega \cos(-u_o - 90°)$;

(III) Positions and Speeds of Satellite Platforms at Instant τ*

In the system Oe-XpYpZp, one has:

$$\overrightarrow{r_0} = (R_e + H),0,0)^T \qquad (4)$$
$$\overrightarrow{V_0} = (0,\sqrt{\mu/(R_e + H)},0)^T$$

(IV) I Kinetics Models

In the Oe-XIYIZI system, I movement differential equations are:

(5)
$$\begin{cases} \dot{X}_I = -\mu X_I / r^3 + a_{TX} \\ \ddot{Y}_I = -\mu Y_I / r^3 + a_{TY} \\ \dot{Z}_I = -\mu Y_I / r^3 + a_{TZ} \end{cases}$$

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In this:

$$r = \sqrt{X_I^2 + Y_I^2 + Z_I^2}$$

aTX, aTY, and aTZ act as thrust accelerations used on unit masses.

When thrust accelerations are 0, I is in free flight.

At the instant τ*=0, satellite platforms release I. Due to the fact that the XI and Xp axes are congruent, as a result, the initial I location vector $\vec{r}_1$ and the initial satellite platform vector are the same. $\vec{r}_1 = \vec{r}_0 = (R_e + H, 0.0)^T$
If one adopts thrust impulse assumptions that I, at the instant τ*=0, achieves velocity increase amounts $\overline{\Delta V}$ and record is made of $\overline{\Delta V}$ in the system Oe-XI YI ZI expressed as $\overline{\Delta V}$ = $(\Delta V_{XI}, \Delta V_{YI}, \Delta V_{ZI})^T$, then, the initial velocity in system Oe - XI YI ZI can be expressed as:

(6) $$\begin{bmatrix} \dot{X}_{I0} \\ \dot{Y}_{I0} \\ \dot{Z}_{I0} \end{bmatrix} = \begin{bmatrix} \Delta V_{x1} \\ \Delta V_{y1} \\ \Delta V_{z1} \end{bmatrix} + B^{-1}\overline{V}_{tt}$$

(VI) SS Kinematic Models

Assuming that, at the instant τ*=0, SS is located at position S and flies at the instant τ* just to position S(illegible), then, the geocentric angle spread between S and S(illegible) is (illegible). S(illegible) is the predicted hit point. At the instant τ(illegible), the SS position vector in Oe -XYZ is $(R_e+H_g,0,0)'$, then, in the system Oe-XIY(illegible)ZI, expressed as:

(7) $$\overline{r}_2 = (AB)^{-1}(R_e + H_g,0,0)'$$

III. IMPULSE VELOCITY GAIN GUIDANCE

In the intercept orbit coordinate system Oe - XI YI ZI, the I position vector is $\overline{r}_1$. The SS position vector is $\overline{r}_2$.

Then, delta f is already known, as shown in Fig.1. At instant τ(illegible) =0, satellite platforms release I. Then, I possess the platform velocity $\overline{V}_0$. In the system Oe -XI YI Z(illegible), it is expressed as $B^{-1}\overline{V}_0$. After that, by thrust impulses supplied instantaneously by propulsion systems it carries itself, I is made to achieve a velocity gain of $\overline{\Delta V}$. Then, I changes instantaneously from velocity $B^{-1}\overline{V}_0$ to

$\overline{V}_r$. $\overline{V}_r$ is designated as the necessary velocity, that is, with I flying along the intercept path and--at the instant τ*--hitting the predetermined hit point S*, the required velocity at instant τ* =0. After solving for $\overline{V}_r$, one obtains $\overline{V}_0$ = $\overline{V}_r - B^{-1}\overline{V}_0(\overline{V}_r$ ($\overline{V}_0$ is the

$(\dot{X}_{10}, \dot{Y}_{10}, \dot{Z}_{10})^T$) described above).

Due to $\overline{V}_0$, it is possible to surpass the second cosmic velocity. As a result, intercept orbits can be a certain type of circular conic curve--ellipse, parabola, or hyperbola.

Below, use is made of Herrick methods in order to precisely determine intercept orbits and required velocities Vr . Herrick methods first surmise that intercept orbit semiparameters Po associated with setting out from point B at instant τ* and passing through point S* are--due to $\overline{r_1}, \overline{r_2}$ --already known quantities. Therefore,

(8) $$\cos\Delta f = \overline{r_1} \cdot \overline{r_2} / r_1 r_2$$

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(9) $$r_n = P / (1 + e\cos f_n) \qquad n = 1,2$$

One then has

$$\begin{aligned} e\cos f_n &= P / r_n - 1 \qquad n = 1,2 \\ e\sin f_1 &= (e\cos f_1 \cos\Delta f - e\cos f_2)\sin\Delta f \\ e\sin f_2 &= (e\cos f_1 - e\cos f_2 \cos\Delta f)\sin\Delta f \end{aligned}$$

Therefore, it is possible to solve for

$$\begin{aligned} f_n &= \mathrm{arctg}(e\sin f_n / e\cos f_n) \qquad n = 1,2 \\ e &= \left[(e\cos f_1)^2 + (e\sin f_1)^2 \right]^{1/2} \end{aligned}$$

Due to

$$
\begin{cases}
\sin E_n = r_n \sin f_n \cdot \sqrt{1-e^2} \, / \, P \\
 & n = 1.2. \quad e < 1 \quad \text{ellipse} \\
\cos E_n = r_n (e + \cos f_n) \, / \, P \\
\sinh H_n = r_n \sin f_n \cdot \sqrt{e^2 - 1} \, / \, P \\
 & n = 1.2. \quad e > 1 \quad \text{hyperbole} \\
\cosh H_n = r_n (e + \cos f_n) \, / \, P
\end{cases}
$$

Therefore, one has

$$
\begin{cases}
E_n = \operatorname{arctg}(\sin E_n \, / \, \cos E_n) & n = 1.2 \quad e < 1 \quad \text{ellipse} \\
H_n = \operatorname{arctg}h(\sinh H_n \, / \, \cosh H_n) & n = 1.2 \quad e > 1 \quad \text{hyperbole} \\
F_n = \operatorname{tg}(f_n \, / \, 2) & n = 1.2 \quad e = 1 \quad \text{parabola}
\end{cases}
$$

$$a = P / (1 - e^2)$$

Make

$$
\begin{cases}
M_n = E_n - e\sin E_n & n = 1,2 \quad e < 1 \quad \text{ellipse} \\
M_n = e\sinh H_n - H_n & n = 1,2 \quad e > 1 \quad \text{hyperbole} \\
M_n = (F_n + F_n^3 / 3) / 2 & n = 1.2 \quad e = 1 \quad \text{parabola}
\end{cases}
\tag{10}
$$

Then /44

(11)
$$\begin{cases} \tau^* = \sqrt{a^3/\mu}(M_2 - M_1) & e < 1 \text{ ellipse} \\ \tau^* = \sqrt{-a^3/\mu}(M_2 - M_1) & e > \text{ hyperbola} \\ \tau^* = \sqrt{P^3/\mu}(M_2 - M_1) & e = \text{parabola} \end{cases}$$

If the τ^* solved for and given values are not equal, then, corrections are made to guessed P values, and the operations described above are repeated until the difference between τ^* solved for and given values satisfies accuracy requirements and they are stopped.

In a case where intercept orbit semiparameter P is already known, it is then possible to solve for Vr components in the system Oe - XI YI ZI as:

$$V_r = \begin{bmatrix} \dot{X}_1 \cdot r \\ \dot{Y}_1 \cdot r \\ \dot{Z}_1 \cdot r \end{bmatrix} = \begin{bmatrix} \frac{\mu}{P} \frac{(\frac{P}{r_1} - 1)\cos\Delta f - (\frac{P}{r_2} - 1)}{\sin\Delta f} \\ \sqrt{\mu P}/r_1 \\ 0 \end{bmatrix}$$

(12)

Thus, the size of required velocity gains can be precisely determined from the equations below:

(13)
$$\overline{\Delta V} = \overline{V}_r - B^{-1}\overline{V}_0$$
$$\Delta V = |\overline{\Delta V}|$$

Due to limitations on the fuel I carries, if the maximum velocity impulse I propulsion systems are capable of supplying is delta Vmax , then it is required that

(14)
$$\Delta V < \Delta V_{max}$$

Besides this, attention should also be paid to the fact that I is only suitable as an interception device for flight outside the atmosphere. If the interception orbit during the process of flying from B to S has a minimum altitude from the surface of the earth of Hm , then it is required that

(15)
$$H_m > 100\mathrm{km}$$

IV. METHODS TO PRECISELY DETERMINE τ^* THREAT AREAS, τ^* DEFENSE AREAS, AND τ^* INTERCEPT AREAS

(I) Precise Determination of τ^* Threat Areas

During the process of SS intercept, I undergoes restrictions associated with the two equations (14) and (15). As a result, there are only I carried on satellite platforms within a fixed range which then possess the capability to kill or damage SS at instant τ^*. This is the threat area with regard to SS. Due to satellite platforms making circular orbital movements, threat areas are, therefore, a section of spherical surface using (Re+H) as its radius.

At instant τ^* =0, the angular location of satellite platform B relative to S can be described using the two angles δ_u, $\delta\omega$. See Fig.2. Using the center of the earth as the center of the sphere and (Re + H) to be the radius, a sphere is made. The projection on it of the north pole of the earth acts as the north pole of this sphere. SS on the projection is S. The projection of the predicted hit point is S*. A meridian line is made through S. Again, through B, make a great circle perpendicular to the meridian line at B'. Let the spherical surface angles 2

$\widehat{BB'} = \delta u$, and $\widehat{SB'} = \delta\omega$, be used to describe the location of satellite platform B relative to S. Based on a knowledge of spherical triangles, it is not difficult to obtain the relationships between δu, $\delta\omega$ and Ω, uo, and τ^*.

When $-90^\circ < u_o < 0^\circ$,

$$\beta = \arccos[\cos u_o \cos(\Omega + n_{ss}\tau^*)]$$
$$\angle BSB' = 90° + \arcsin(\sin u_o / \sin\beta)$$

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$$\delta\omega = \arcsin(\sin\angle BSB' \sin\beta) \cdot \mathrm{sing}(\Omega)$$
$$\delta u = -\arccos(\cos\beta / \cos\delta\omega)$$

When $-270° < u_o < -90°$,

$$\delta\omega = -\arcsin[\sin(\Omega + n_{ss}\tau^*)\sin(-u_o - 90°)]$$
$$\delta u = -90° - \arccos[\cos(-u_o - 90°) / \cos\delta\omega)]$$

Using δu to be the transverse coordinate and $\delta\omega$ to be the longitudinal coordinate while stipulating δu north of the equator as positive and $\delta\omega$ east of the meridian plane to be positive, it is possible to solve for the τ^* threat area

associated with platforms in direct motion is as shown in Fig.3(a). The τ^* threat area associated with platforms in retrograde motion is as shown in Fig.3(b).

(II) Precise Determination of τ^* Defense Areas

After the given intercept period τ^*, for each given uo, it is possible to obtain angular distances S relative to satellite platform orbit surfaces as $(\Omega+nss\tau^*)$. Because Ω exists within a certain range, $(\Omega+nss\tau^*)$, therefore, also has an interval. It is displayed as a section of circular arc on the equator (because SS is only capable of moving on the equator). This is the τ^* defense area. Defining uo north of the equator as positive, S east of the platform orbit surface as positive, and taking $(\Omega+nss\tau^*)$ as the longitudinal coordinate and Uo as the transverse coordinate, it is then possible to obtain τ^* defense areas associated with a series of uo as shown in Fig.3(c) (direct motion platform) and Fig.3(d) (retrograde platform).

(III) Precise Determination of τ^* Intercept Areas

Intercept areas are collections of all possible predicted hit points. On the equator they are also displayed as a circular arc section. Positions of predicted hit points relative to I are described using Ω and uo. Each given individual uo corresponds to a range associated with a certain Ω. Taking Ω to be the longitudinal coordinate and uo to be the transverse coordinate,

it is then possible to obtain τ^* intercept areas associated with a series of uo as shown in Fig.3(e) (direct motion platforms) and Fig.3(f) (retrograde motion platforms).

CONCLUSIONS

1. As far as interception devices which are carried by low altitude satellite platforms with orbital altitudes of 640km and possessing velocity gains of roughly 6km/s are concerned, they are capable of intercepting equatorial stationary satellites. In accordance with current technology levels, this type of small interception device is capable of realization. As a result, equatorial stationary satellites face a real threat.

2. There is a relationship between the size of threat areas, defense areas, and intercept areas and intercept time periods. The smaller τ^* is, the smaller the zones then are. Conclusions clearly show that, when intercept time periods are smaller than 4x103 s, interception capability still exists. However, within this time period--with the help of advanced warning, reconnaissance, and other similar means--SS still has adequate time to adopt a number of effective counter interception measures.

3. The methods and conclusions supplied by this article can be useful in the analysis of space warfare systems.

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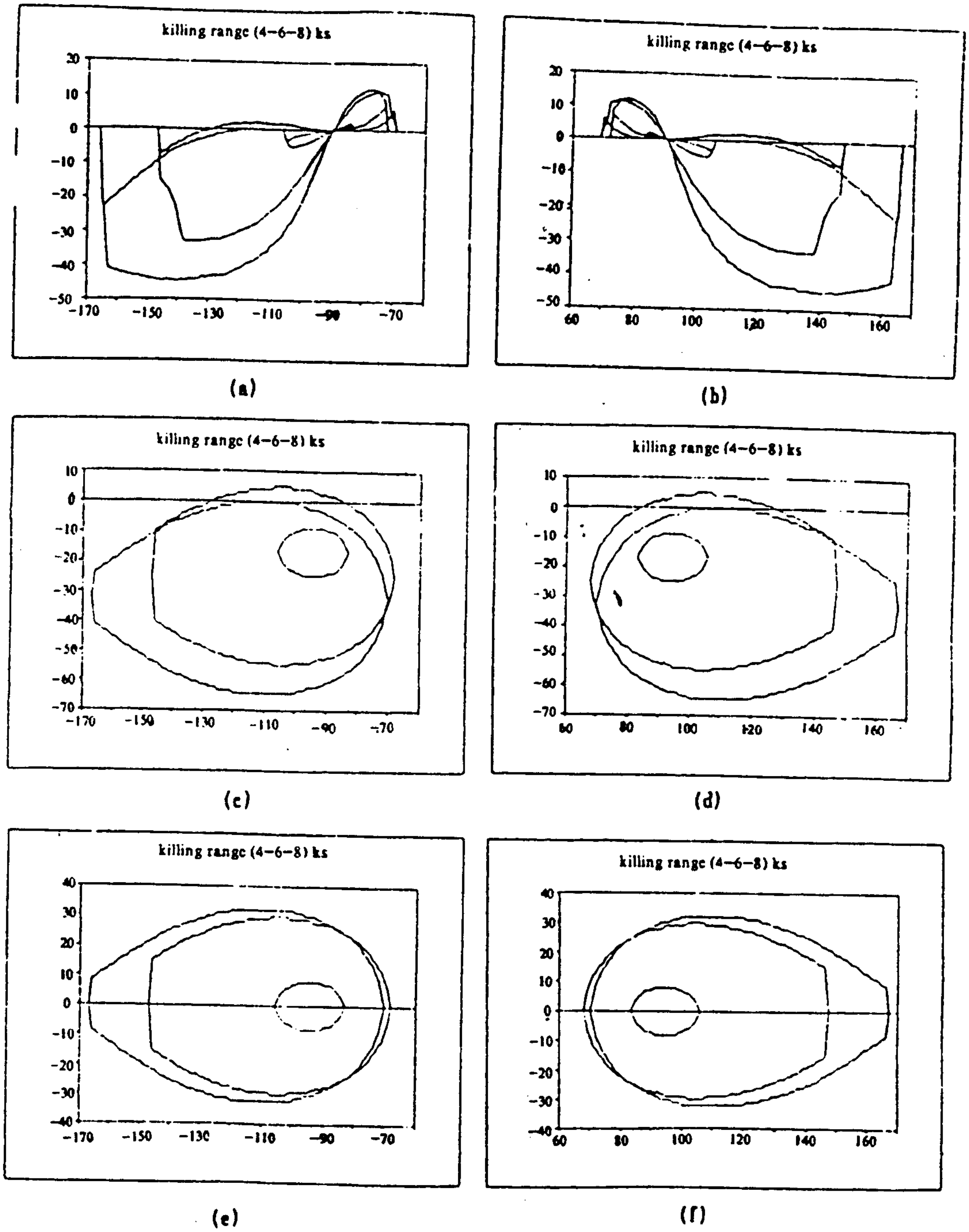

Fig.3 Typical Threat Areas, Defense Areas, and Intercept Areas

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